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SUMMARY

The object of the experiment was to relate the average mass velocity in thin rectangular channels and the velocity sensed by a single fixed total-pressure probe in combination with a fixed static-pressure probe or a wall tap.

Two total-pressure probes and one static-pressure probe with outside diameters of 0.025, 0.050, and 0.050 inch, respectively, were tested individually in the center region of the cross section near the outlet of a thin rectangular channel 0.116 by 2.62 inches in cross section and 30 inches in length. The relation between the velocity indicated by the probes and the average velocity of the fluid over the channel cross section was determined for a range of Reynolds numbers from 3600 to 58,000 and for a variety of positions of the total-pressure probe from the surface of the broad walls. The flow at the channel outlet for this Reynolds number range was turbulent and fully developed.

The large diameter of the probes, relative to broad plate spacing, did not affect the ability to measure the local velocities in the center regions. The indicated velocities were unaffected by yaw for small angles below $\pm 5^{\circ}$ for the 0.050-inch probe and $\pm 15^{\circ}$ for the 0.025-inch probe.

The static-pressure probe was found to sense a pressure that was 2.5 to 3.0 percent of the velocity head (based on average channel velocity) higher than the wall tap. The yaw effect was negligible for angles up to $\pm 15^{\circ}$.

Thus, it is concluded from these results that the combination of a single fixed total-pressure probe and a static-pressure probe or a wall tap can be employed to measure, within 2 percent, the flow rate in thin rectangular cooling passages such as those commonly used in many nuclear reactors.

INTRODUCTION

This report is concerned with the relation between the true average velocity inside a thin rectangular channel and the velocity that is indicated by the combination of a single fixed total-pressure tube and a fixed static-pressure probe that is situated in the flow stream (or a wall tap). This relation and other flow characteristics of the probes were experimentally studied, and the results are reported herein.

The experiments were motivated by the need to know the flow rates inside various cooling passages of the NASA Plum Brook Reactor, in particular, the need to know, within about 3 percent, the flow rates inside the rectangular cooling passages of the fuel assemblies in the core. Without adequate cooling in these and other channels throughout the core, the reactor would become overheated in any place where a flow deficiency would exist.

The adequacy of flow in the various cooling passages of a reactor can only be found, with sufficient accuracy, by direct measurements. Direct measurements are very difficult primarily because the reactor is compact and the flow passages are small and not readily accessible. The space limitations severely restrict the size and amount of any instrumentation that can be employed. For these reasons it is advantageous to use the fewest and the simplest instruments without sacrificing accuracy in the value of the measured flow rates. One of the simplest flow-measuring devices that proved to be accurate and was successfully employed in the NASA Plum Brook Reactor (ref. 1) was a total-pressure tube in conjunction with a static-pressure probe or a wall tap.

To utilize a single total-pressure tube with a static probe or a wall tap for the accurate determination of the flow rate within a channel depends on one important factor. Somehow the velocity that is calculated from the measured pressure difference between the total-pressure probe and the static probe or static wall tap must be related to the average value. (This calculated velocity will be referred to herein as the indicated velocity.) If the channel is long and of a constant regular geometric shape, such as annular, rectangular, or circular, and if the probe is located far enough from the inlet so as to be in a fully developed flow field, the relation between the average and the indicated velocity can be found. If the velocity distribution is well known, such as that in a pipe, then the relation can be estimated from the available data with reasonable accuracy, otherwise the relation must be found by direct experimentation. For irregularly shaped passages (and there are few in a reactor) the indicated velocity can not usually be related to the actual flow pattern without a very elaborate experimental study on a model because the fluid motion is usually unknown and erratic. Because the NASA Plum Brook Reactor and many others similar to it contain mostly thin rectangular passages and some thin annular cooling channels, the flow-measuring problem centers chiefly on channels of these shapes.

Two other factors for consideration in the use of a total-pressure tube and a static probe or a wall tap were the location of these along the channel length and in the flow-passage cross section and the size of the probe in relation to the smallest dimension, which was the broad-plate spacing of the rectangular passage. The center of the channel cross section near the outlet was chosen as the most suitable location for the total-pressure probes because the velocity profile there is fully developed and is close to that measured by Whan and Rothfus (ref. 2) in a similar but much larger rectangular channel than the one used in this experiment. The static-pressure probes and the wall taps were always placed far enough laterally from the total-pressure tube to avoid mutual interference between them, generally about 20 probe diameters (1 in.) away. The probe diameter had to be large relative to the plate spacing in order to reduce the response time of the probe during a test. With the total-pressure probes no longer of negligible size relative to the broad-plate spacing, it seemed reasonable to assume that the probe could disturb the flow pattern in the vicinity of the probe in such a way that it no longer would sense the undisturbed total pressure at a point. Instead it would sense some lower average value over the probe mouth.

There appears to be no literature available on the relation between the average velocity and the velocity indicated by a total-pressure probe whose diameter is large compared with the rectangular channel broad-wall spacing, which is very small. A work that is closely related to this problem was performed by Whan and Rothfus (ref. 2) in a rectangular duct 14 by 0.7 inch in cross section (aspect ratio 20:1). A 0.058-inch-outside-diameter total-pressure tube was used to traverse only the center region between the broad walls. The velocity profile was integrated and a plot of the ratio of this integrated average to the maximum velocity was made. Plots of the ratio of local to maximum velocity against the Reynolds number were included along with other results. The integrated average is not the same as the average velocity for the entire cross section because of the reduced velocities adjacent to the narrow end walls. These investigators were interested in the case of infinite parallel plates; hence only the center region between the broad walls was investigated. Since no average velocities for the entire channel were given, the measured point velocities could not be related to the average values. (In the reactor flow tests (ref. 1), the results of reference 2 were used to estimate a first approximation to the ratio of the average to the indicated velocity, until the results of the work in this report became available.)

It was the object of this experiment to determine the relation between the average and the indicated velocities under conditions approximating those that existed during the tests described in reference 1. A flow channel measuring 0.116 by 2.62 inches in cross section and 30 inches in length was used as a model of a typical cooling channel in the fuel assemblies, and two total-pressure probes and one static-pressure probe were tested in this channel. The working fluid was water at 80° F, and its velocity in the channel ranged from about 1.5 to 30 feet per second.

The total-pressure probes were tested at various positions between one broad wall and the channel center. Tests were also performed with the static-pressure probe in the center of the channel cross section to determine the relation (if any existed) between the pressure sensed by the probe and that sensed by the wall tap under the same water temperature and velocity conditions as for the total-pressure probes. All probes were checked for the influence of misalinement by yawing them relative to the water flow direction.

APPARATUS

Schematic drawings showing the essential features of the test equipment are shown in figures 1 and 2. The details of the rectangular channel in which the probes were tested is shown in figure 1. The total-pressure probes and the static-pressure probe, which were each tested individually in the channel, are shown in figure 2. The pressures sensed by each probe were compared with that sensed by the static wall tap shown in the figure. In these experiments as in the reactor flow tests the wall tap was placed far enough laterally

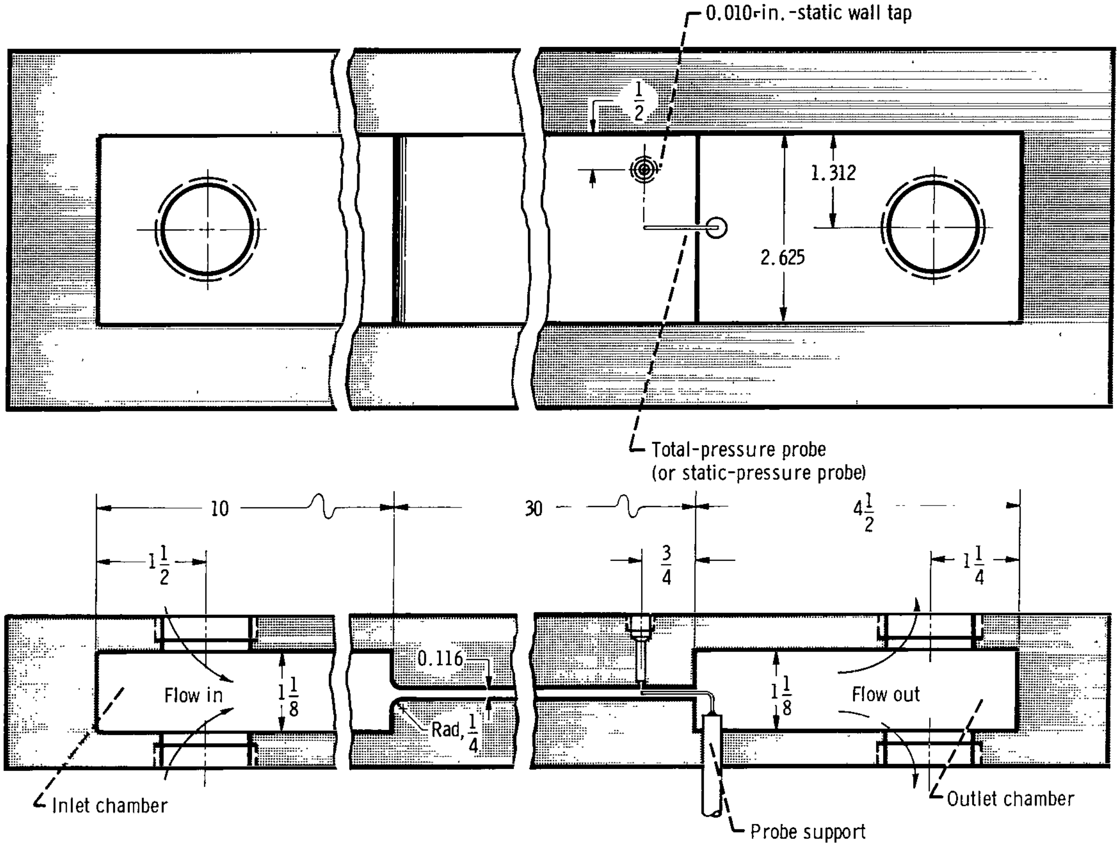

Figure 1. - Test section used to investigate total-and static-pressure probes. Probe holder and actuator not shown. (All dimensions in inches.)

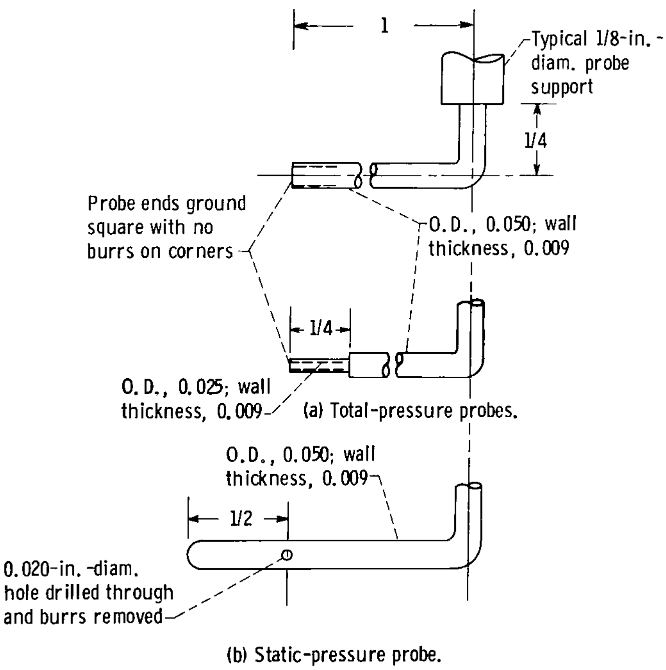

Figure 2. - Details of probes. (Dimensions in inches.)

(20 probe diam. or more) from the probe location to avoid influences caused by the presence of the probe. A probe actuator (not shown in fig. 1) was located on the outside surface of the test section and was used to drive the probe and hold it at any position between the broad walls. The position of a probe was measured relative to the surface of one of the broad walls with a dial indicator that was accurate to 0.001 inch. The pressure difference between the wall tap and the probe being tested was measured with U-shaped manometers containing water or water on mercury. The manometer scales were divided into increments of 0.1 inch.

All tests were conducted in a water flow loop that was specially designed to calibrate flowmeters. The flow rate was very steady and was measured to within 1/4 percent of the true value. A typical test with a total-pressure probe was made by setting the probe at some predetermined distance away from one broad wall and recording data for various water flow rates. Then, the probe was moved to a new position and the test was repeated.

In the tests to measure the effect of probe misalinement the angle between the probe-tube axis and the flow direction was changed by rotating each probe about the support axis while holding it fixed relative to the broad walls. These misalinement tests were conducted at one midrange velocity with each probe positioned midway between the broad walls.

DATA PROCESSING

The average velocity in the channel was calculated from the continuity equation by using the measured value of the mass rate of flow, the channel cross section, and the water density:

$$V_A = \frac{M}{\rho A}$$

(All symbols are defined in the appendix.)

The indicated velocity was evaluated by applying the familiar relation for a total-head probe to the measured pressure difference between the total-pressure probe and the wall pressure tap:

$$V_I = \sqrt{\frac{2}{\rho} (P_T - p_w)}$$

The Reynolds number of the flow in the channel is based on the average water velocity V_A and the equivalent diameter D, where

$$D = \frac{4(ab)}{2(a + b)}$$

RESULTS

In figures 3 and 4 are given the results of the tests in a channel conducted on total-pressure probes 0.025 and 0.050 inch in diameter in the turbulent Reynolds number range from about 3600 to 58,000 at various positions between the broad walls. Included in figures 3 and 4 is the curve of the ratio of average to maximum velocity V_A/V_M for flow between infinite parallel plates as measured by Whan and Rothfus (ref. 2) with a 0.058-inch-diameter probe in a channel whose broad walls were 0.7 inch apart. In general, the results for both figures exhibit the same trends, namely, that the ratio of V_A/V_I (1) increases rapidly with increasing Reynolds number in the range between 3600 and 10,000 and then more slowly above 10,000 and (2) is a minimum when the total-pressure tube is situated midway between the broad walls. As

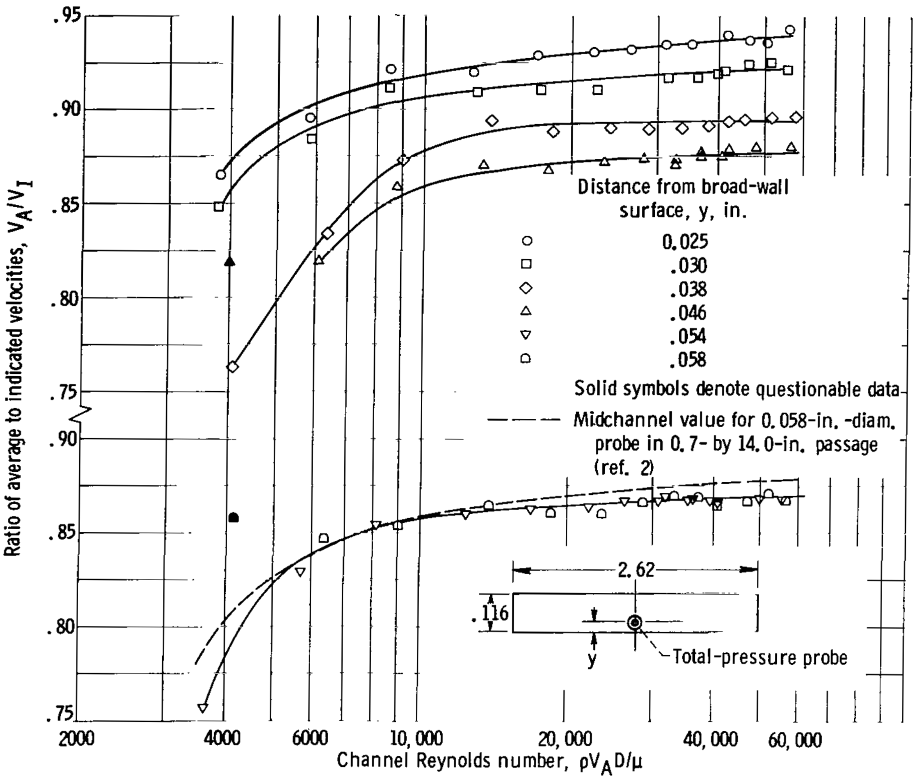

Figure 3. - Relation between ratio of average to indicated fluid velocity and channel Reynolds number for 0.025-inch-diameter total-pressure probe.

the probes are positioned closer to a broad wall, they indicate a velocity that is closer to the average velocity; that is, V_A/V_I increases above the minimum. The larger probe (0.050 in. diam.) senses a velocity closer to the average when located close to a wall than does the smaller probe (0.025 in. diam.), whose axis is at the same position. When the larger of the two probes is touching the wall, the probe mouth center is 0.025 inch from the surface and the opening extends from 0.005 to 0.040 inch from the wall. As a result, a contribution to the average impact pressure is made by the lower velocities nearer the wall. When the smaller of the two probes has its axis at the same distance from the surface (0.025 in.), the probe mouth opening does not extend as far into the region of slower moving fluid as does the larger probe; hence, the indicated velocity is higher (and the V_A/V_I lower) than for the larger probe. No tests could be run with the 0.025-inch probe against the wall because of probe geometry, but it is certain that the probe would indicate velocities closer to the average because the entire probe opening would be in the regions of lower flow. The V_A/V_I data of figures 3 and 5 that were taken at the midchannel region from 0.046 to 0.058 inch from the reference wall agree within about $\pm 1\frac{1}{2}$ percent with the curve given in reference 2 for a probe located at exactly the midchannel except for Reynolds Numbers less than 8000. At a Reynolds number of 4000 the accuracy was reduced because the measured velocity pressures were about 1 inch of water and were subject to greater error. Hence, two data points (at $y = 0.046$ and 0.058 and a Reynolds number of approx. 4100) were not included in the curve fitting.

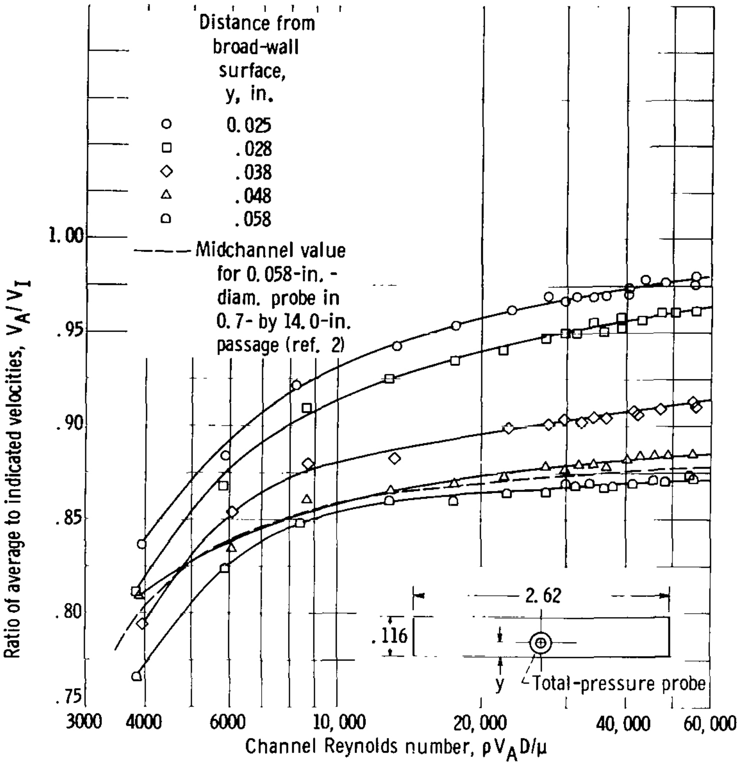

Figure 4. - Relation between ratio of average to indicated fluid velocity and channel Reynolds number for 0.050-inch-diameter total-pressure probes.

When a total-pressure probe is used to measure the average flow through channels similar to the one tested here, the results of figures 3 and 4 show that the probe must be positioned with care, preferably near the channel center, where the exact location is not as critical as it is closer to the wall.

Figure 5 presents a comparison of the velocities measured in these experiments with the velocity profile of Whan and Rothfus at a Reynolds number of 11,600 and the 1/7th power profile. The results given in figures 3 and 4 for Reynolds numbers of 11,600 and 50,000 were picked off the fitted curves and recalculated to give the ratio V/V_M. The value at the channel center, y = 0.058, was divided by the V_A/V_I values for each distance y from a wall; that is, $V/V_M = (V_A/V_I)_{y=0.058}/(V_A/V_I)_y$. Each V_I was assigned to the y of the probe center.

It is noted that the velocities measured in this experiment in a small channel with relatively large-diameter probes (ratios of broad-wall spacing to probe diameter of 2.3 and 4.65) agree within about ±3 percent with the profile measured by Whan and Rothfus in a 0.70-inch-wide passage with a much smaller probe, of 0.058-inch diameter (ratio of broad-wall spacing to probe diameter of 12.1). This agreement suggests that the large probes do measure the local velocities with reasonable accuracy in the midchannel region; hence, the probe size is not an important factor.

The influence of probe misalinement on the indicated velocity was checked, but only for the case when the probe was situated midway between the two broad walls. The total-pressure probe was rotated about its support so that the probe was yawed relative to the direction of flow. At a Reynolds number of 36,000, the 0.025-inch-probe readings were not affected by yawing for angles up to ±15°, and the 0.050-inch-probe readings were not affected up to ±5°. Hence, the small amount of misalinement that is unavoidable when mounting a total-pressure tube in a channel will not cause any error in the measured velocity.

The effect of yaw is of interest because in application a static probe cannot be precisely alined with a zero yaw angle. When the static-pressure probe was positioned in the exact center of the passage with the probe taps facing the narrow side walls and the probe was directed straight into the flow stream with a yaw angle equal to zero, the data showed that the probe sensed a higher pressure than the wall tap by about 2.5 to 3.0 percent of the velocity head $\rho V_A^2/2$ over the entire range of Reynolds numbers. The static probe was relatively insensitive to yaw angles up to 15° at a Reynolds number of 36,000. Above 15° a sudden change in difference between probe and wall-tap pressure readings occurred. The cause of the sudden change may well have been a flow separation along the downstream side of the probe. Likewise the blockage effect due to yawing was not detectable up to 15° of yaw.

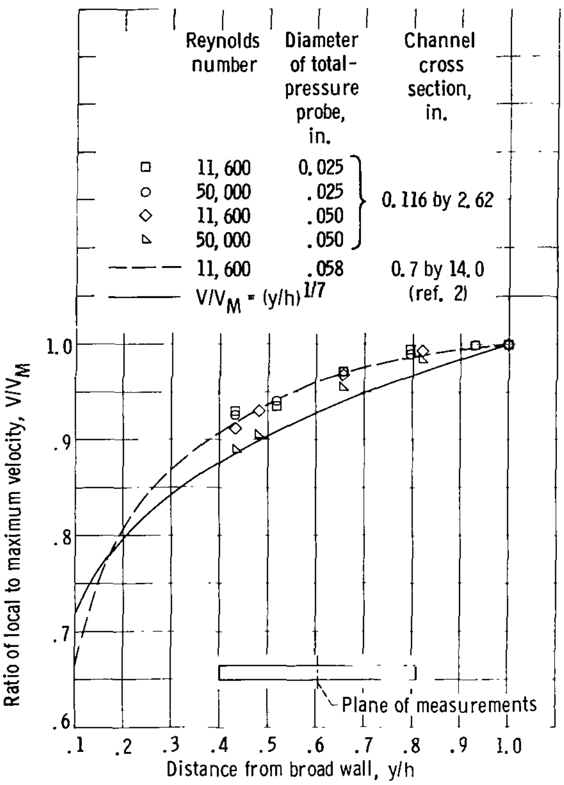

Figure 5. - Dimensionless velocity profile between two broad walls of rectangular channel with aspect ratios of 20 and 22.6.

CONCLUSIONS

When a total-pressure tube in combination with a static-pressure probe or a wall tap is used to measure the flow rate in small thin rectangular channels, the relation between the indicated and average velocities must be known if the flow rate is to be accurately determined. The experiments described in this report have shown that the relation is dependent primarily on the probe position relative to the broad-wall surface and the Reynolds number, and less on the precise probe alinement with the direction of flow and the probe diameter. If a static-pressure probe with the static holes located so that they face the narrow channel walls is used in place of a wall tap, the probe will record a static pressure that is higher than the wall tap value by 2.5 to 3.0 percent of the velocity pressure. A static-pressure-probe-reading was found to be relatively unaffected when the probe was yawed less than 15° to the flow stream.

These results show that it is possible to use the combination of a single fixed total-pressure probe and a static-pressure probe or a wall tap to measure within 2 percent the flow rate in thin rectangular cooling passages of nuclear reactors.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, September 3, 1964

APPENDIX - SYMBOLS

A cross-sectional area of rectangular channel

a length of short sides of rectangular channel

b length of long sides of rectangular channel

D equivalent diameter of rectangular channel, $4ab/2(a + b)$

h half-spacing between broad walls, $a/2$

M mass rate of flow

P_T total pressure sensed by total-pressure probe

p_w static pressure sensed by static wall tap

V local velocity at a point

V_A average velocity over channel cross section

V_I velocity indicated by total-pressure probe

V_M maximum velocity at center of channel

w specific weight of fluid

y transverse coordinate measured from broad-wall surface

μ viscosity

ρ fluid density

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